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A. G. Stanley

Degradation of CdS Thin Film Solar Cells in Different Environments

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ABSTRACT

CdS thin film solar cells were operated under different bias conditions for periods of six months in the following environments: vacuum thermal cycling between $-160^{\circ}C$ and $60^{\circ}C$, constant illumination in vacuum and in dry oxygen at $60^{\circ}C$. The results were compared to the degradation of test cells in synchronous orbit. It was concluded from the observed changes in the I-V characteristics that the degradation is caused primarily by a combination of light and temperature and not by purely thermal stresses. The presence of a vacuum does not appear to be a significant contributory factor to the ultimate degradation of the cells.

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

DEGRADATION OF CdS THIN FILM SOLAR CELLS IN DIFFERENT ENVIRONMENTS

INTRODUCTION

Cadmium sulfide thin film solar cells are subject to several intrinsic degradation mechanisms that gradually reduce their electrical output over long periods of time[1-5]. It has so far been possible to identify only one of these mechanisms, the development of shorts by copper nodule formation when the cells are operated at open circuit voltage[4,5]. This mechanism should not apply when the solar cells are operated at maximum power or at even lower output voltages. Other failure modes are associated with the cell construction. This is indicated by the steady increase in the long term stability of the cells over the past few years by improvements in processing and process controls.

It has been customary to subject cadmium sulfide solar cells to vacuum thermal cycling tests on the assumption that degradation is produced primarily by thermal stresses that damage the structure of the device. Comparative long term tests of one type of cell in several different environments have not been carried out, though they are of fundamental importance in the evaluation of the devices for different applications. Such tests face the difficulty that sequential tests on cells from the same production lot take up to two years to perform, by which time the devices themselves are obsolete. It was considered worthwhile to take

this risk in order to demonstrate the effects of different environments. The results are not representative of devices produced today.

In the experiments under review it was decided to compare the degradation produced by the following environments:

1. Vacuum thermal cycling between -160^{o} and 60^{o} C, illumination during hot cycle
2. Constant illumination in vacuum at 60^{o} C
3. Constant illumination in dry oxygen at 60^{o} C

60^{o} gives an upper limit to the equilibrium temperature of a self-deployed CdS thin film solar cell array in synchronous orbit. The vacuum environment under steady state illumination is most representative of this space environment except during solar eclipse. The tests in dry oxygen were carried out to determine the effect of the presence of oxygen on the degradation mechanism, but this environment also has significance for terrestrial applications.

EXPERIMENT

It had previously been noted[6] that long cycles produce far more degradation than short cycles over the same temperature range. For this reason a cycling period of 3 hours was chosen, equally divided between hot and cold temperature ranges. The vacuum during cycling and during constant illumination was maintained at 10^{-6} torr.

The cells were suspended from a bakelite frame by their negative contact and were heated and cooled radiatively. The temperature was measured by means of thermocouples bonded to the center of each cell. Temperature fluctuations within $\pm 6^{o}C$ occurred during the thermal cycling tests due to variations in the liquid nitrogen supply used for cooling. The constant temperature tests at $60^{o}C$ employed water cooling which produced a steadier cell temperature.

The cells were illuminated at air mass zero equivalent light intensity which provided the sole source of heat. The light intensity was monitored by a silicon solar cell. Darkening of the xenon lamp with time causes a slight shift in the spectral distribution which was measured by means of a spectrometer. However, this effect was not large enough to produce any change in the ratio of the outputs from a silicon and from a cadmium sulfide standard cell.

There were four test positions available. Three of the cells were loaded at the initial maximum power point near 0.31 V by means of a fixed load resistor across the cell. The voltage across the cell under the constant load gradually decreased as the cell degraded. The remaining cell was kept at open circuit voltage and degraded severely as the result of localized short circuits as previously described[4,5].

I-V curves were measured in situ at intervals throughout the test under an accurate light intensity setting corresponding to air mass zero. Care was taken not to bias the cells at negative voltages during the measurements. The circuit described by Brandhorst and Hart[7] was employed. The curves were swept in both directions from short-circuit current to open circuit voltage in order to detect hysteresis effects. All the solar cells were taken from the same batch of 3" x 3" cells fabricated in March 1968, and independently tested at the Boeing Company[8]. While not as good as solar cells supplied for testing more recently, these cells represent a substantial improvement over earlier devices. The cells were selected at random and were of comparable quality regarding output, fill factor, series and shunt resistance.

RESULTS AND DISCUSSION

The changes produced in maximum power, short circuit current and open circuit voltage under the three environmental conditions studied are shown in Figs. 1 through 9. The range of values obtained from the 3 cells tested under load are indicated by vertical lines. The results obtained on thermal cycling in vacuum (Figs. 1-3) are comparable to those obtained at the Boeing Company[8], but the average degradation is more severe. Recent Boeing tests on improved CdS cells produced maximum power degradations from 6 to 17 percent after 4200 cycles[9]. The

Boeing cycle consists of one hour of light followed by 30 minutes of darkness. In the light portion of the cycle the cells reached an equilibrium temperature near 60°C in about 20 minutes. During the dark portion of the cycle, the temperature of the cells dropped rapidly, reaching values below -100°C in 30 minutes. In the present cycling tests, the cells were kept 1-1/2 hours under illumination and 1-1/2 hours in darkness. It took only 5 minutes for the cells to reach their equilibrium temperature near 60°C and 30 minutes to drop below -100°C.

Earlier tests[6] indicated that longer cycles are more damaging. Long time constants are associated with electronic trapping phenomena[10] and also with the thermoelastic properties of the substrate and adhesives used in the cell construction. It should also be noted that some of the cells cycled under load exhibited transient shorts on several occasions in the course of the test, indicating severe damage. At the end of 703 cycles, the cells were still degrading though at a reduced rate.

Cells tested in vacuum at 60°C underwent a very severe degradation in maximum power as well as in the other parameters (Figs. 4-6). However, the degradation appears to be quite comparable to the degradation under thermal cycling shown in Figs. 1-3, if it is assumed that all the damage is incurred at the high temperature, so that 1 day corresponds to 16 cycles. These equivalent cycles are shown in Figs. 4-6. The degradation

appears to have stopped after about 100 days, but by this time the maximum power output had dropped to between one quarter and one half of the original value.

On two occasions the test had to be stopped for two days due to malfunction of the equipment. The first break occurred after 41 days and the cells were exposed to the atmosphere. This produced a very marked annealing of the damage. The second break occurred after 119 days. This time the cells were not exposed to the atmosphere and the interruption caused no change in the device characteristics. Furthermore, there was no annealing on exposure to the atmosphere at the end of the test after 138 days. It had been noted in earlier thermal cycling experiments carried out by the author that the initial degradation is reversible, whereas after several months exposure the degradation is irreversible. These results indicate two different types of degradation mechanisms. The reversible degradation is electronic in nature and may be associated with trapping states possessing long lifetimes, such as have been observed by Lindmayer[10] in these cells. The irreversible degradation is probably electrochemical in nature.

The results of the test in dry oxygen, Figs. 7-9, show some very interesting effects. After about 35 days the degradation levels off at a value roughly equal to the degradation obtained toward the end of the thermal cycling test. Following a two day interruption of the illumination after 71 days all the cells

continued to degrade right up to the end of the test after 165 days. The degradation at the end of this test was somewhat more severe than that at the end of the vacuum test.

Two possible inferences may be drawn from the oxygen test. One is that the thermal cycling test would also have shown a significant further degradation had the test been continued beyond 1600 cycles corresponding to 100 days at 60°C. The second postulated by Shiozawa[11] is that oxygen gradually reduces the short-circuit current at temperatures as low as 60°C due to a reaction of cuprous sulfide with oxygen. A comparison of Figs. 5 and 8 does indeed confirm a drastic decrease in short circuit current beyond 80 days in dry oxygen. Shiozawa also suggests[4] that the supply of residual oxygen in a vacuum at 10^{-6} torr might be sufficient to promote this degradation. This argument can be countered by the results of experiments carried out in space. Figure 10 shows the degradation in short circuit current of CdS solar cells, 1 cm x 2 cm, flown on LES-5 and LES-6 in synchronous orbit[12]. The degradation of these cells is similar to but less severe than that produced in the vacuum test shown in Fig. 5. In the satellite experiments, the solar cells were body mounted and operated at a temperature of 15°C, whereas the cells were kept at 60°C during the vacuum test. A comparison of the slopes of the two curves leads to an activation energy of 0.2 eV for the degradation process, which explains the absence of deterioration at -160°C during thermal cycling.

Figures 11 and 12 show the fill factor on light exposure in a vacuum and dry oxygen respectively for the same cells as above. The decrease in fill factor is somewhat greater in vacuum. The fill factor of the cells subjected to thermal cycling degraded by the same amount as the cells exposed to steady illumination in vacuum, again assuming the 16 cycles are equivalent to one day. The decrease in fill factor indicates an increase in series resistance which could be due to delamination within the cell structure, formation of cracks in the cuprous sulfide layer or copper diffusion. The latter would have to be enhanced by the light generated electric field, since Shiozawa[4] estimates that in the dark the diffusion degrades the cell output by only 10% in 3 to 5 years.

CONCLUSIONS

By comparing the degradation produced in cadmium sulfide thin film solar cells by exposure to constant illumination from a xenon lamp at a temperature of 60°C to that produced by thermal cycling, it is concluded that the degradation is caused primarily by a combination of light and temperature and not by purely thermal stresses acting on the cell structure. An exposure of the cells to light at constant normal operating temperature, therefore, provides a more meaningful real time simulation of the performance of thin film solar cells suspended in a lightweight array on a space satellite in synchronous orbit. The presence

of a vacuum does not appear to be a significant contributory factor to the ultimate degradation of the cells. The quantitative results do not reflect the performance of cadmium sulfide cells in current production.

ACKNOWLEDGMENT

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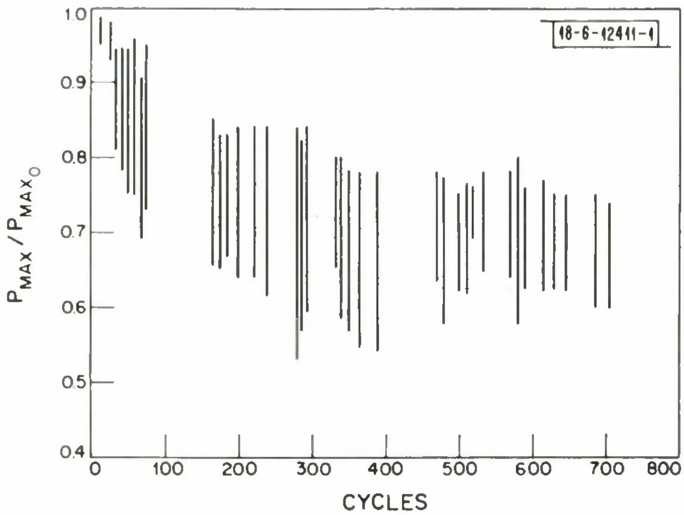

Fig. 1. Change in maximum power under vacuum thermal cycling. The lines indicate the range of values obtained from cells cycled under load corresponding to initial maximum power load from -160 to 60°C.

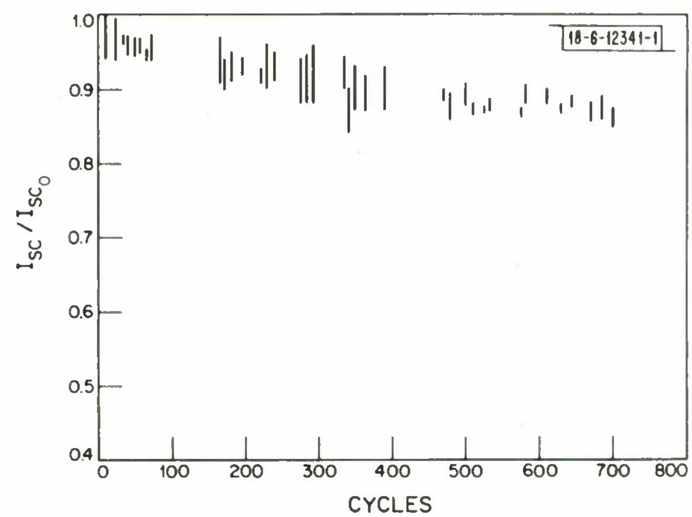

Fig. 2. Change in short circuit current under vacuum thermal cycling. Conditions as in Fig. 1.

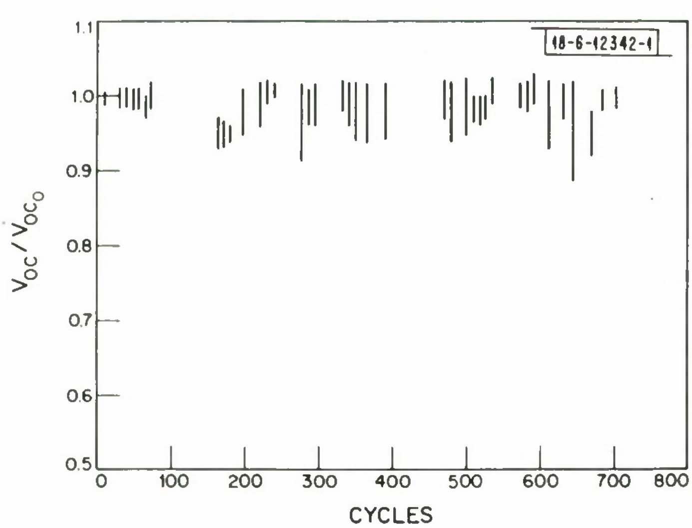

Fig. 3. Change in open circuit voltage under vacuum thermal cycling. Conditions as in Fig. 1.

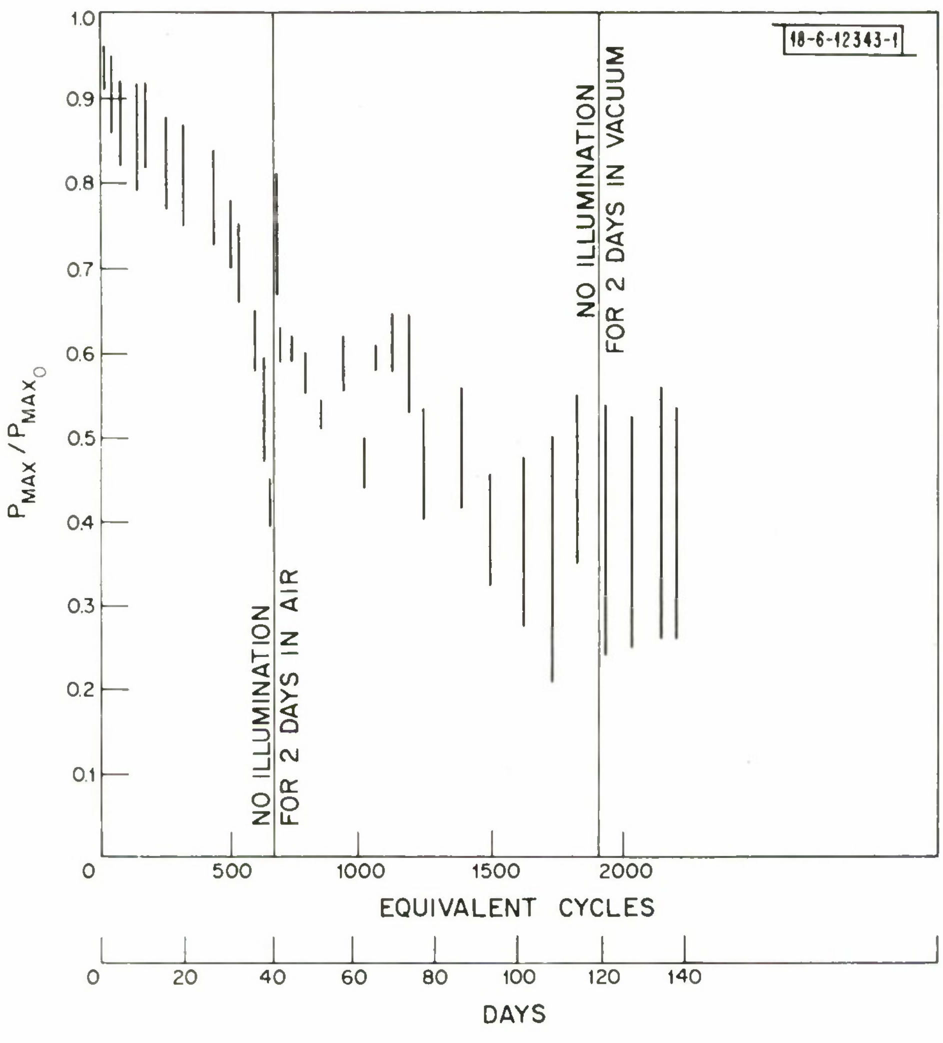

Fig. 4. Change in maximum power in vacuum under constant illumination. The lines indicate the range of values obtained from cells illuminated under load corresponding to initial maximum power load over a temperature range from 50 to 70°C.

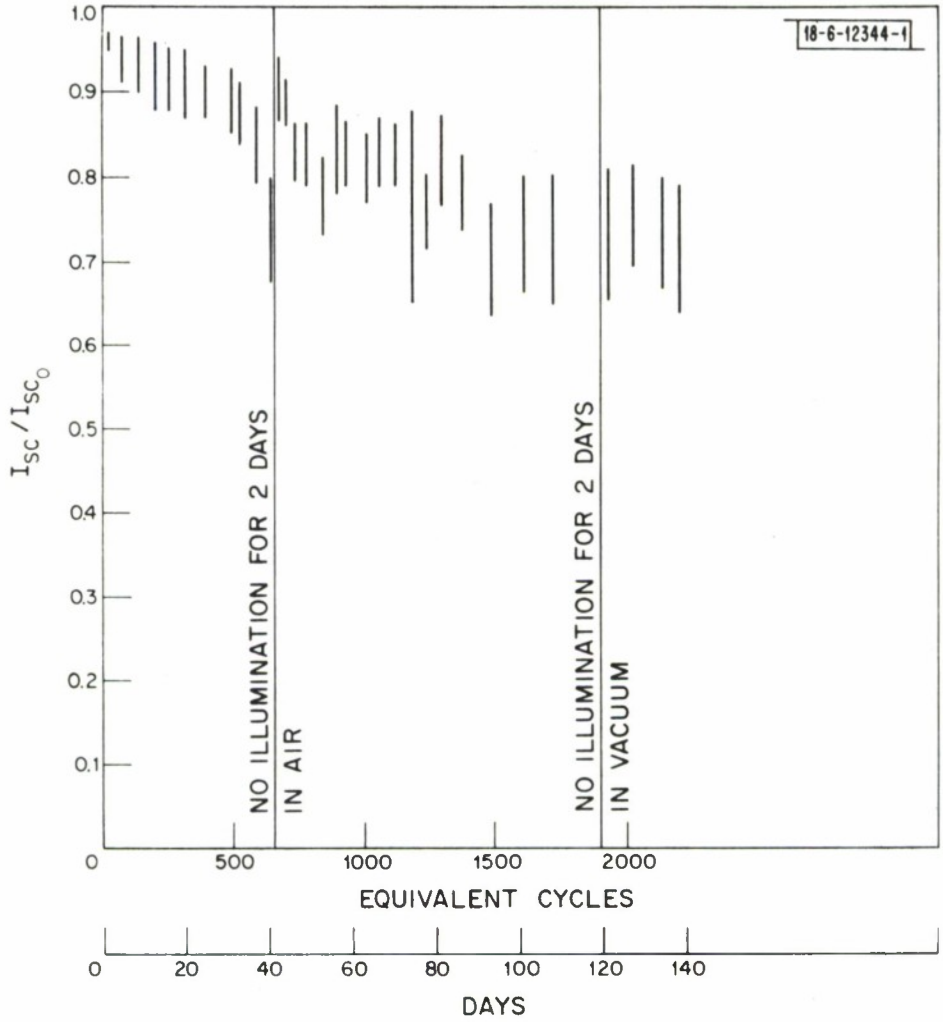

Fig. 5. Change in short circuit current in vacuum under constant illumination. Conditions as in Fig. 4.

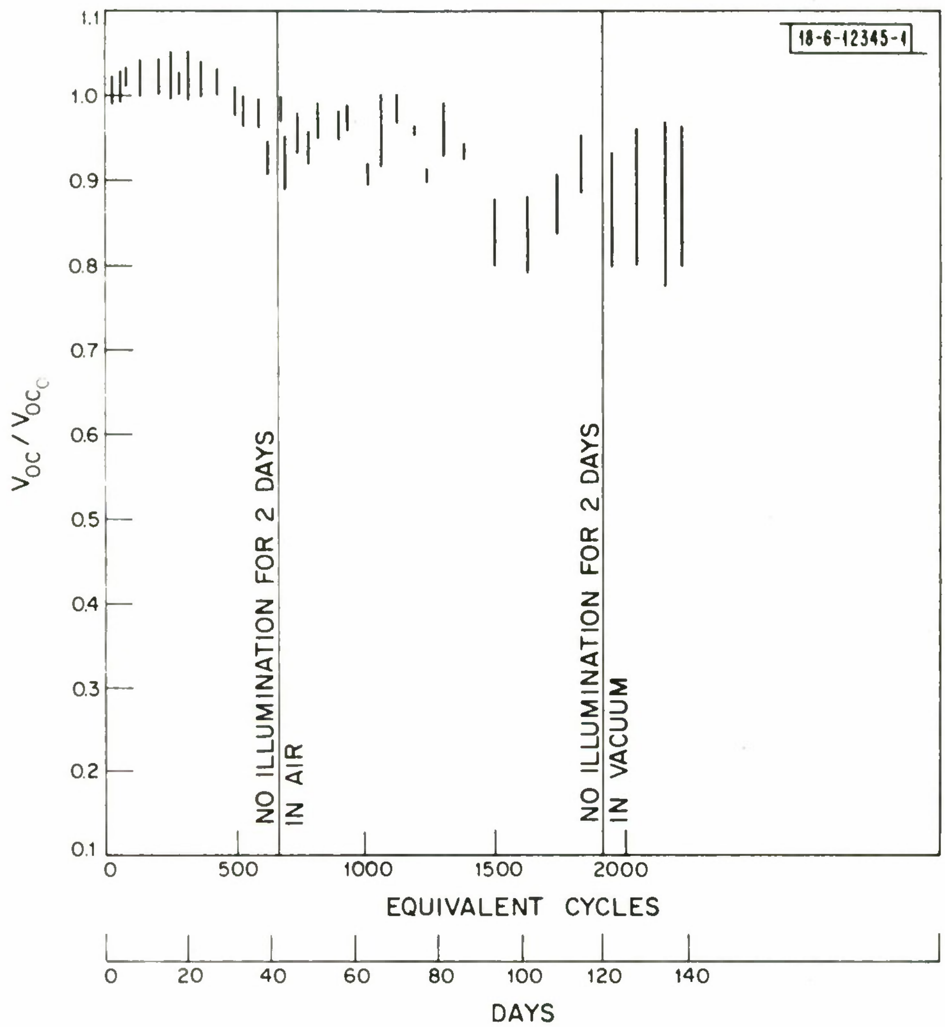

Fig. 6. Change in open circuit voltage in vacuum under constant illumination. Conditions as in Fig. 4.

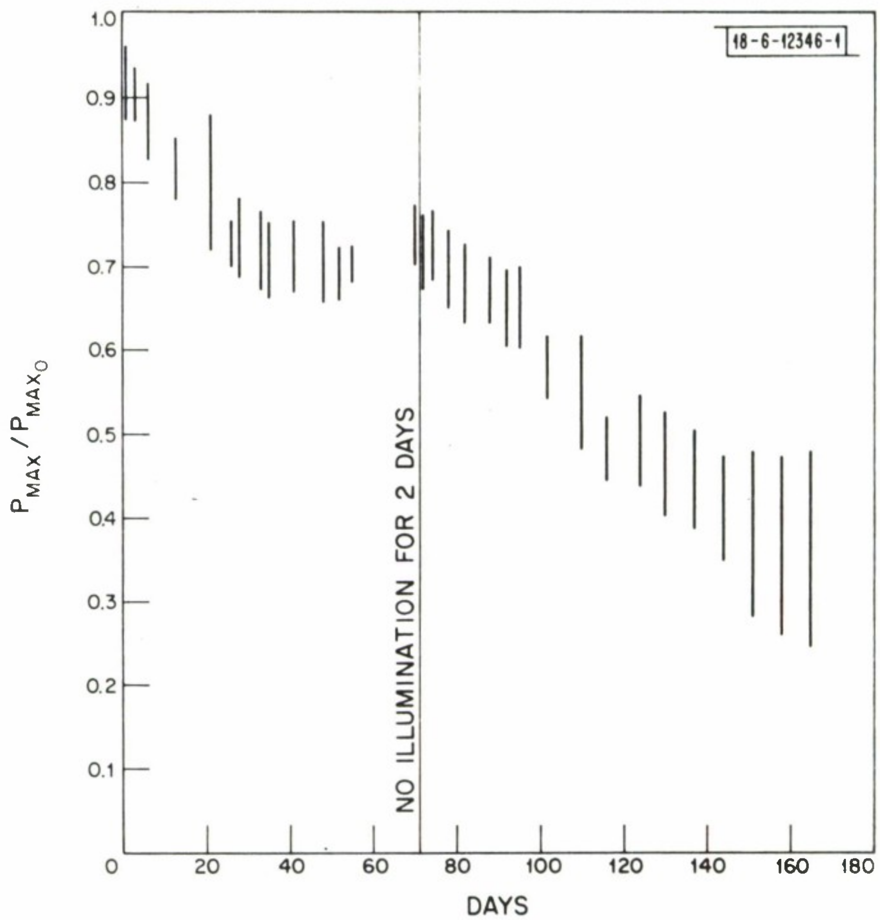

Fig. 7. Change in maximum power in dry oxygen under constant illumination. The lines indicate the range of values obtained from cells illuminated under load corresponding to initial maximum power load over a temperature range from 60 to 64°C.

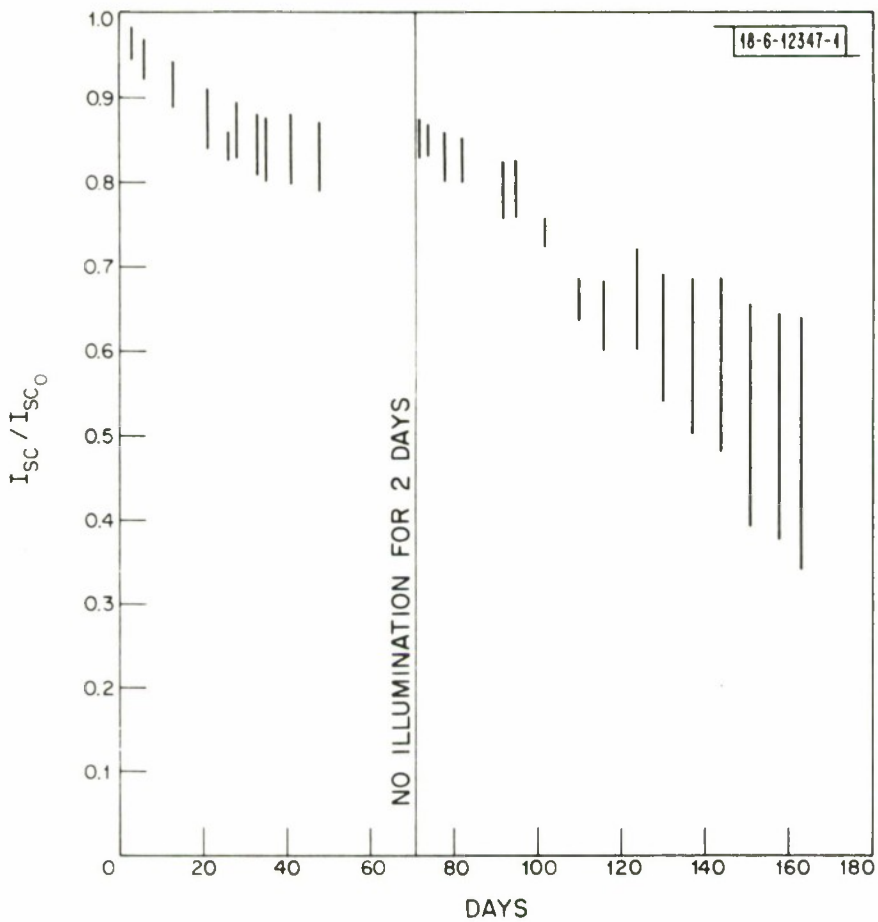

Fig. 8. Change in short circuit current in dry oxygen under constant illumination. Conditions as in Fig. 7.

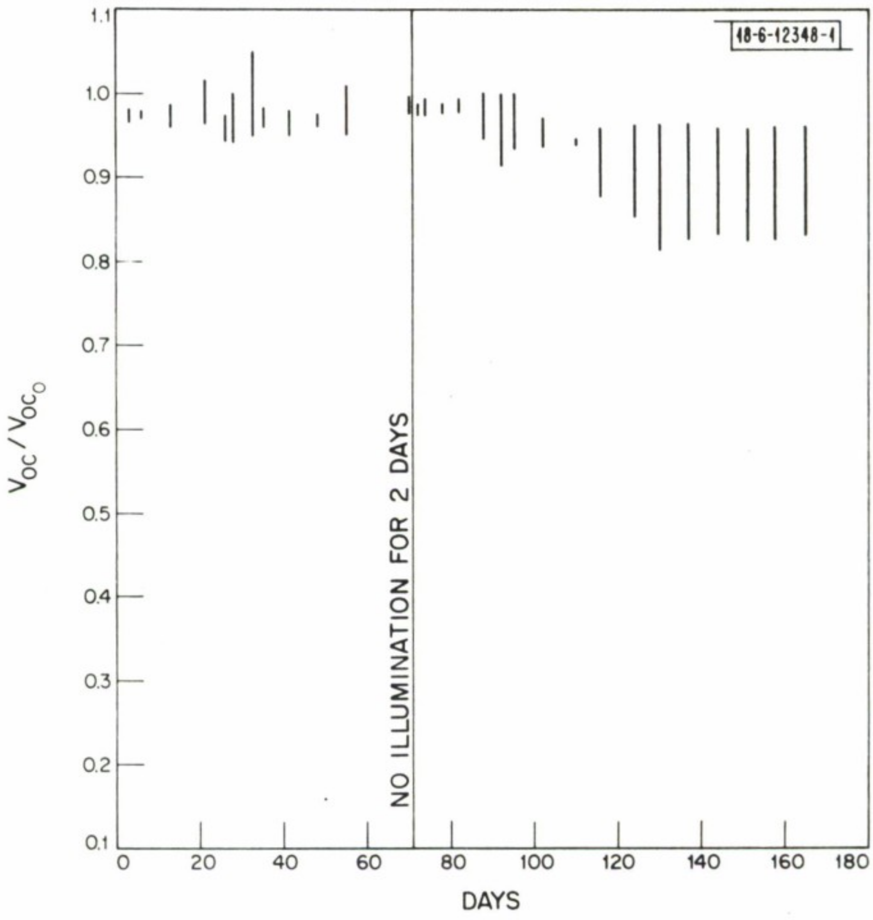

Fig. 9. Change in open circuit voltage in dry oxygen under constant illumination. Conditions as in Fig. 7.

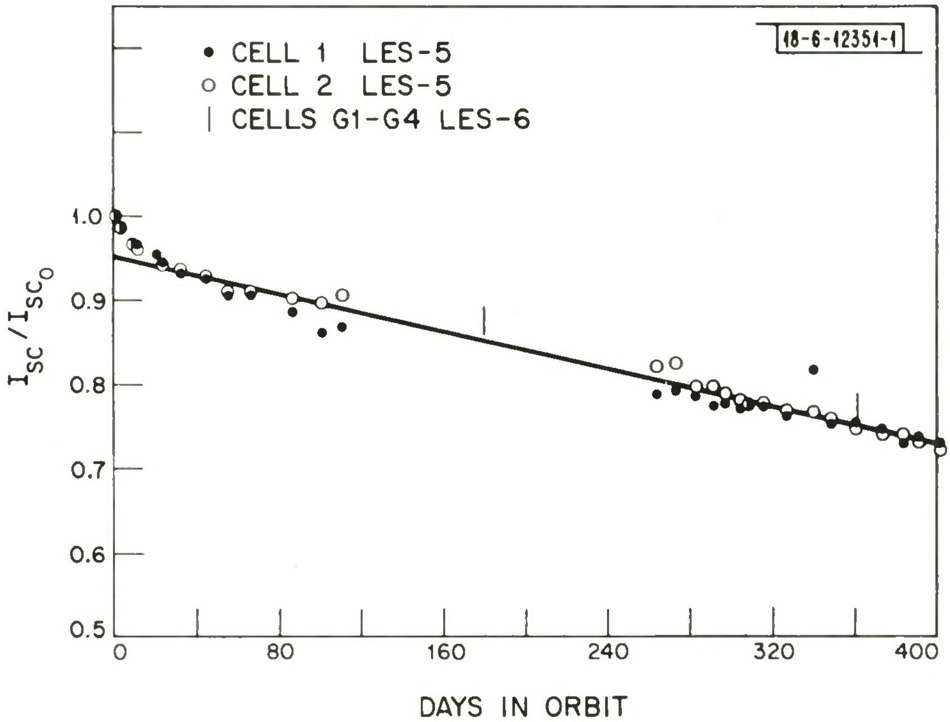

Fig. 10. Change in short circuit current of CdS solar cells on LES-5 and LES-6 in synchronous orbit.

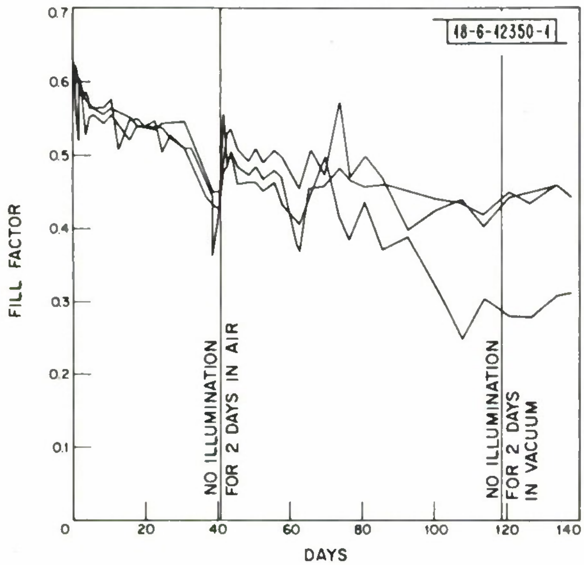

Fig. 11. Fill factor vs time in vacuum under constant illumination. Cells illuminated under load corresponding to initial maximum power load over temperature range from 50 to 70°C.

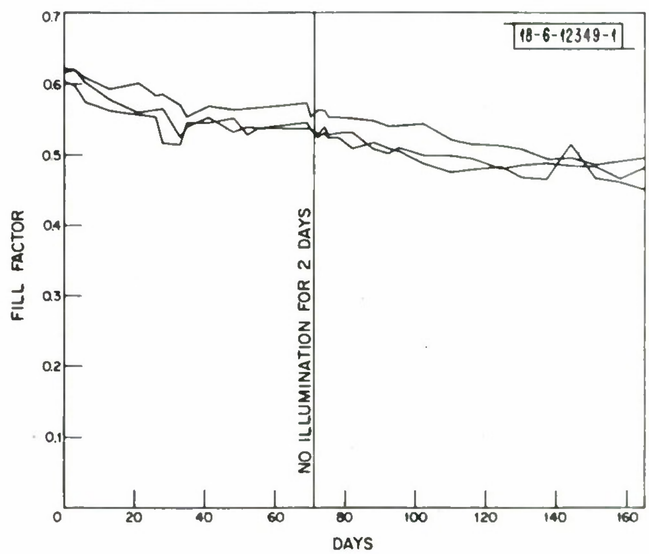

Fig. 12. Fill factor vs time in dry oxygen under constant illumination. Cells illuminated under load corresponding to initial maximum power load over temperature range from 60 to 64°C.

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13. ABSTRACT

CdS thin film solar cells were operated under different bias conditions for periods of six months in the following environments: vacuum thermal cycling between −160° and 60°C, constant illumination in vacuum and in dry oxygen at 60°C. The results were compared to the degradation of test cells in synchronous orbit. It was concluded from the observed changes in the I-V characteristics that the degradation is caused primarily by a combination of light and temperature and not by purely thermal stresses. The presence of a vacuum does not appear to be a significant contributory factor to the ultimate degradation of the cells.

14. KEY WORDS

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